REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
21-05-2014	Final Report	1-May-2011 - 30-Apr-2014

4. TITLE AND SUBTITLE
Free-Surface Fluid-Object Interaction for the Large-Scale Computation of Ship Hydrodynamics Phenomena: Final Report

5a. CONTRACT NUMBER
W911NF-11-1-0083

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
Yuri Bazilevs

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of California - San Diego
9500 Gilman Drive
MC 0934
La Jolla, CA 92093 -0934

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
57917-MA.13

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
The overarching objective of this work is to develop and implement a robust, accurate and scalable numerical methodology for simulating air-water free-surface flow, fluid-object interaction (FOI), and fluid-structure interaction (FSI) phenomena for complex geometries, and with no limitations on the motion of the free surface, and with particular emphasis on ship hydrodynamics. The following specific research objectives were identified for this project: 1) Development of a theoretical framework for free-surface flow, FOI and FSI that is a suitable starting point for discretization with Finite Element or Isogeometric methods; 2) Development of computational procedures

15. SUBJECT TERMS
free-surface flow; isogeometric analysis; fluid-structure interaction

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Yuri Bazilevs
UU	UU	UU	UU		19b. TELEPHONE NUMBER 858-534-3663

Report Title

Free-Surface Fluid-Object Interaction for the Large-Scale Computation of Ship Hydrodynamics Phenomena: Final Report

ABSTRACT

The overarching objective of this work is to develop and implement a robust, accurate and scalable numerical methodology for simulating air-water free-surface flow, fluid-object interaction (FOI), and fluid-structure interaction (FSI) phenomena for complex geometries, and with no limitations on the motion of the free surface, and with particular emphasis on ship hydrodynamics. The following specific research objectives were identified for this project: 1) Development of a theoretical framework for free-surface flow, FOI and FSI that is a suitable starting point for discretization with Finite Element or Isogeometric methods; 2) Development of computational procedures (i.e., geometry modeling, meshing, and analysis software) in support of this framework with emphasis on surface ship hydrodynamics; 3) Verification and Validation of the implemented numerical technology on the well-known benchmark examples and lab-scale and full-scale surface vessels.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/07/2013	6.00	J. Kvandal, J. Spinks, J. Dunaway, Y. Bazilevs, I. Akkerman. Toward free-surface modeling of planing vessels: simulation of the Fridsma hull using ALE-VMS, Computational Mechanics, (08 2012): 719. doi: 10.1007/s00466-012-0770-2
07/07/2013	12.00	I. Akkerman, K. Benner, Y. Bazilevs. Free-Surface Flow and Fluid-Object Interaction, MARINE 2011, IV International Conference on Computational Methods in Marine Engineering: Selected papers, (03 2013): 49. doi:
07/07/2013	11.00	Y. Bazilevs, M.-C. Hsu, I. Akkerman, D.J. Benson. Enabling Computational Methods for Offshore Wind Turbines, MARINE 2011, IV International Conference on Computational Methods in Marine Engineering: Selected papers, (03 2013): 105. doi:
07/07/2013	10.00	M. Ruess, D. Schillinger, Y. Bazilevs, V. Varduhn, E. Rank. Weakly enforced essential boundary conditions for NURBS-embedded and trimmed NURBS geometries on the basis of the finite cell method, INTERNATION Journal for Numerical Methods in Engineering, (07 2013): 0. doi:
07/07/2013	8.00	YURI BAZILEVS, KENJI TAKIZAWA, TAYFUN E. TEZDUYAR. CHALLENGES AND DIRECTIONS IN COMPUTATIONAL FLUID–STRUCTURE INTERACTION, Mathematical Models and Methods in Applied Sciences, (02 2013): 215. doi: 10.1142 /S0218202513400010
07/07/2013	7.00	D.J. Benson, S. Hartmann, Y. Bazilevs, M.-C. Hsu, T.J.R. Hughes. Blended isogeometric shells, Computer Methods in Applied Mechanics and Engineering, (03 2013): 133. doi: 10.1016/j.cma. 2012.11.020
08/27/2012	4.00	I. Akkerman, Y. Bazilevs, D. J. Benson, M. W. Farthing, C. E. Kees. Free-Surface Flow and Fluid-Object Interaction Modeling With Emphasis on Ship Hydrodynamics, Journal of Applied Mechanics, (01 2012): 0. doi: 10.1115/1.4005072
08/27/2012	5.00	Andre?s E. Tejada-Marti?nez, Ido Akkerman, Yuri Bazilevs. Large-Eddy Simulation of Shallow Water Langmuir Turbulence Using Isogeometric Analysis and the Residual-Based Variational Multiscale Method, Journal of Applied Mechanics, (01 2012): 0. doi: 10.1115/1.4005059
TOTAL:		**8**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. Y. Bazilevs. Multiscale Methods in FSI and Applications. Invited Lecture at a Multiscale Methods Worksop - a Conference celebrating Wing Kam Liu's 60th Birthday, Evanston, IL, July 22-23, 2012

2. Y. Bazilevs. Enabling Computational Technology for Offshore Wind Turbines. Plenary Lecture at the IVth International Conference on Computational Methods in Marine Engineering (MARINE2011), Lisbon, Portugal, Sept. 28-30, 2011

3. Y. Bazilevs, I. Akkerman, J. Dunaway, M.W. Farthing, C.E. Kees, J. Kvandal, and J. Spinks. Free-Surface Flow and Fluid-Object Interaction with Emphasis on Ship Hydrodynamics. Invited Lecture at the IVth International Conference on Computational Methods in Marine Engineering (MARINE2011), Lisbon, Portugal, Sept. 28-30, 2011

4. Y. Bazilevs. Fluid—Structure Interaction Modeling for Offshore Wind Turbines. Plenary Lecture at IXth Deep Sea Offshore Wind R&D Seminar (DeepWind2012), Trondheim, Norway, January 19-20, 2012

5. K. Benner, I. Akkerman, and Y. Bazilevs. Residual-based variational multiscale free-surface flow and fluid/structure-interaction using isogeometric analysis. 6th Southern California Symposium on Flow Physics, UC Santa Barbara, April 14, 2012

6. Y. Bazilevs. Isogeometric Analysis for Multi-Physics Applications. Invited Lecture at a Workshop on Advanced Computational Engineering, MFO, Oberwolfach, Germany, February13-17, 2012

7. Y. Bazilevs, "Modern Computational Fluid—Structure Interaction at Multiple Scales", Invited Presentation, NanoMacroMega Workshop, UC San Diego, September 12—14, 2012

8. Y. Bazilevs, "Computing Aerodynamics and Fluid--Structure Interaction of Wind Turbines", Mechanical Engineering Seminar, UC San Diego, October 1, 2012

9. Y. Bazilevs, "Aerodynamics and Fluid-Structure Interaction Modeling of Wind Turbines", Invited Presentation, T.J.R. Hughes Young Investigator Symposium at IMECE 2012, Houston, TX, November 9-15, 2012

10. Y. Bazilevs, "Computational fluid-structure interaction: Blood pumps, surface ships, and wind turbines", Semi-Plenary Lecture, ACM 2013 – A Conference Celebrating the 70th Birthday of Thomas J.R. Hughes, San Diego, CA, February 24-27, 2013

11. Y. Bazilevs, "Advances in Isogeometric Analysis of Structures, Fluids, and FSI", Invited Presentation, Workshop on Multiscale Methods Celebrating the 70th Birthday of Ted Belytschko, Evanston, IL, April 18-20, 2013

12. Y. Bazilevs, Invited Lecturer at the Short Course "Isogeometric Methods for Numerical Simulation", International Center for Mechanical Sciences, Udine, Italy, May 20-24, 2013

13. Y. Bazilevs, "Computational Fluid-Structure Interaction: From Blood Pumps to Wind Turbines", Semi-Plenary Lecture, 12th US National Congress on Computational Mechanics (USNCCM12), Raleigh, NC, July 22-25, 2013

Number of Presentations: 13.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/27/2012	1.00	Yuri Bazilevs, Ido Akkerman, David Benson, Christopher Kees, Matthew Farthing. Free-Surface Flow and Fluid-Object Interaction Modeling With Emphasis on Ship Hydrodynamics, Journal of Applied Mechanics (03 2011)
08/27/2012	2.00	Andres Tejada--Martinez, Ido Akkerman, Yuri Bazilevs. Large-Eddy Simulation of Shallow Water Langmuir Turbulence Using Isogeometric Analysis and the Residual-Based Variational Multiscale Method, Journal of Applied Mechanics (03 2011)
08/27/2012	3.00	I. Akkerman, J. Dunaway, J. Kvandal, J. Spinks, Y. Bazilevs. Toward free-surface modeling of planing vessels: simulation of the Fridsma hull using ALE-VMS, Computational Mechanics (08 2012)

TOTAL: **3**

Number of Manuscripts:

Books

Received	Paper
07/07/2013	9.00 Yuri Bazilevs, Kenji Takizawa, Tayfun E. Tezduyar. Computational Fluid-Structure Interaction, Chichester, UK: John Wiley & Sons, Ltd, (01 2013)
TOTAL:	**1**

Patents Submitted

Patents Awarded

Awards

US Association for Computational Mechanics Gallagher Young Investigator Award, 2011

ASME Applied Mechanics Division Thomas J.R. Hughes Young Investigator Award, 2012

Thesis Advisor of Dr. Ming-Chen Hsu who received the inaugural 2013 Chancellor's Dissertation Medal for the best PhD Thesis in the Jacobs School of Engineering at UC San Diego

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Kenneth Benner	0.50	
Ming-Chen Hsu	0.10	
Chris Long	0.10	
FTE Equivalent:	**0.70**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Ido Akkerman	0.75
FTE Equivalent:	**0.75**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Yuri Bazilevs	0.10	
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME	
Kenneth Benner	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Ming-Chen Hsu	
Chris Long	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

1. Developed free-surface flow formulation suitable for discretization by finite elements and Isogeometric analysis.
2. Developed a six degree-of-freedom rigid object formulation and coupled with free-surface flow.
3. Validated free-surface flow for linear FEM and Isogeometric analysis discretizations
4. Developed geometry modeling and meshing capabilities for ship hulls
5. Developed templates to obtain volume parameterization of fluid mechanics domain for ship hulls. Such parameterizations are employed
in the Isogeometric Analysis of free-surface flow
6. Validated the fluid/object-interaction capability using the Fridsma planing hull. The attractive feature of planning hulls is the necessity to
simulate both water and air, since at high speeds the only a small fraction of the planning hull surface is wetted. As a result, the free surface
methodology that does not account for the air domain is not sufficient for this class of problems.
7. Investigated novel structural modeling techniques suitable for the problem class considered in this project.
8. Published six articles in top-tier peer-reviewed international journals, two book chapters, and one book using the research results
generated in this project.
9. Delivered several invited conference presentations and seminars using the research results generated in this project.

The work is directly relevant to the mission of the US Army Corps of Engineers (USACE) in the areas of Coastal Hydraulics and Navigation. Prediction of ship squat, sloshing of liquids (e.g. fuel) in tanks, marine transportation of cargo, evaluation of unsteady loads on
levies and embankments arising due to vessel motion in open channels are of great interest to the USACE.

Other classes of problems include high-speed ship maneuvering in rough seas, high-speed Littoral Combat ships (e.g., Small Waterplane
Area Twin Hull (SWATH) ships), and other situations where the dynamic free surface behavior and wave breaking play a critical role in
the vessel performance and is not accounted for in simplified free-surface models (e.g., free surface approximated by a flat surface with
zero traction boundary conditions). The proposed technology will also be able to provide DoD with detailed flow data that is unattainable
in field tests, yet is critical for optimal ship design.

Technology Transfer